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Long-term hydrological impacts of land use/land cover change from 1984 to 2010 in the Little River Watershed, Tennessee

Chunhao Zhu[1] and Yingkui Li[2]

Abstract

Assessing long-term hydrological impacts of land use/land cover (LULC) change is of critical importance for land use planning and water resource management. The Little River Watershed, Tennessee, is an important watershed supporting drinking water and recreational activities within and around the Great Smoky Mountains National Park in the Unites States. However, the potential hydrological impacts of LULC change, especially urbanization in recent decades, are not quantified. This paper assessed the long-term impacts of LULC change on streamflow and non-point source pollution using the Soil and Water Assessment Tool (SWAT) and a detailed LULC record from 1984 to 2010. The SWAT was first calibrated and validated using observed streamflowin 2010 and then simulated using different LULC patterns in 1984–2010 to quantify the long-term hydrological impacts caused by the LULC change. Simulated results indicated a minor 3% increase in streamflow for the whole watershed from 1984 to 2010, but with a distinct spatial pattern. The increase in streamflow is closely related to urban development. Almost no streamflow increase occurred in the upper watershed within the national park, whereas >10% increase occurred in the lower watershed, especially in areas close to cities. Model simulation also suggested 34.6% reduction in sediment and about 10% reduction in nutrient loads from 1984 to 2010, closely related to the decrease in agricultural land. However, without calibration and validation, the simulated reduction in the sediment and nutrient loads may be problematic because SWAT mainly simulates the static LULC patterns, whereas LULC transitions, such as construction phases, may generate more sediment and nutrient loads. In addition, the simulation also did not account for the sediment and nutrients generated from stream bank erosion.

Key Words: Land use/land cover change, Little River Watershed, Long-term hydrological impacts, SWAT

1 Introduction

Land use/land cover (LULC) change has significant impacts on water quality and quantity such as surface runoff, groundwater, and non-point source (NPS) pollutions over a range of temporal and spatial scales (Bhaduri et al., 2000; Frumkin, 2002; Novotny and Olem, 1994; Weng, 2001; Li and Wang, 2009). Expanded impervious surfaces, such as parking lots, roofs, sidewalks, and driveways, block the precipitation infiltrating into the groundwater and increase the total volume and peak discharge of the stream flow. Excessively eroded sediment from agricultural and construction sites also contributes to NPS pollution, which has become the leading cause of degraded water quality in the U.S. (Bhaduri et al., 2000). NPS pollution [such as nitrogen (N) and phosphorus (P)] is difficult to regulate because such pollutants originate from diffuse rather than point sources (Ezzell et al., 2005). In addition, accumulated sediments and nutrients in streams can adversely impact aquatic eco-systems and impair the use of water for industry, agriculture and drinking purposes (USEPA, 2003; TDEC, 2006; USGS, 2011).

The hydrological impacts of LULC change are usually assessed by a modeling approach, such as EPA Storm Water Management Model (SWMM) (Huber et al., 1988; USEPA, 2011), Long-Term Hydrologic Impact

[1] Master student, Department of Geography, University of Tennessee, Knoxville, TN 37996, USA

[2] Associate Professor, Department of Geography, University of Tennessee, Knoxville, TN 37996, USA. Corresponding author: E-mail: yli32@utk.edu

Assessment (L-THIA) (Harbor, 1994; Li and Wang, 2009), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), and the United States Department of Agriculture (USDA) AGricultural Non-Point Source Pollution Model (AGNPS) (USDA, 2011). Among these models, SWAT has been widely used. For example, Wang et al. (2008) applied it to simulate three land-use scenarios to investigate streamflow variations in Northwest China. Ghaffari et al. (2010) quantified the hydrological response of land use change on surface runoff and groundwater recharge based on SWAT simulation of three-year land-use patterns (1967, 1994, and 2007) in the Zanjanrood Basin in Northwest Iran. Conaghan (2010) used SWAT to compare streamflow and total sediment load between the current (2001) and future (2010) land use scenarios in the Upper Neuse River Basin in North Carolina.

However, most previous studies assessed the hydrological impacts based on a few (two or three) LULC scenarios. Few studies have integrated high-resolution temporal LULC maps derived from remote sensing classification with hydrologic modeling to evaluate the long-term hydrological impacts of LULC change. A detailed LULC record would allow for an accurate assessment of the long-term hydrological consequences of LULC change and provide quantified information for decision makers in land use planning and water resource management. This paper provides a case study from the Little River Watershed, Tennessee, a critical watershed supporting drinking water and recreational activities within and around the Great Smoky Mountains National Park, to assess the long-term impacts of LULC change on streamflow and NPS pollution from 1984 to 2010 using SWAT and a detailed LULC record classified using Landsat images.

2 Study area

The Little River Watershed (LRW), Tennessee, is located around 35°44′N and 83°46′W with a drainage area of approximately 981 km^2 and ranges from 245 m to 2,010 m above sea level. The watershed spans two ecoregions: the Blue Ridge and the Ridge and Valley (Harden et al., 2009; USEPA, 2011). The southeastern portion of the watershed is within the Blue Ridge Mountains with an area of about 517.1 km^2. The soil is deep and well-drained, with metamorphosed sedimentary bedrocks underneath. This portion of the watershed is mainly covered by mixed forest with a world-renowned wondrous diversity of flora and fauna (USNPS, 2011). The northwestern portion of the watershed lies primarily within the Ridge and Valley ecoregion with an area of about 463.4 km^2. It is comprised of multiple layers of shale, limestone, and dolomite (carbonate) bedrock, with fault lines and well developed karst topography (such as sink holes, depressions, and subterranean drainage systems) (King, 1964). Agricultural and urban areas are dominated in this portion. Agricultural land is mainly composed of hay and pasture for livestock and cultivated crops, such as corn, soybeans, and winter wheat (USDA, 2011). Urban areas, including residential and commercial lands, are mainly distributed on the northwest corner of the watershed (Maryville and Alcoa in Blount County). The annual maximum and minimum temperatures were about 20.6 °C and 7.7°C, respectively, from 1966 to 2010. The average annual precipitation was about 1,344 mm. Both temperature and precipitation vary significantly with the altitude (Shanks, 1954). Most precipitation events, such as showers and thunderstorms, were recorded in February, March, and July (USNPS, 2010). More snow falls at higher elevations in the mountains from December to March.

The Little River is a scenic perennial stream about 96.6 km long and is a northwest-flowing tributary of the Tennessee River (Fig. 1). Its water quality varies within each portion of the river. The headwaters within the Great Smoky Mountains National Park have outstanding water quality (USEPA, 2005). However, the lower portion of the stream flowing through urban areas such as Maryville and Alcoa has been affected by urban development. Some tributaries experienced water quality degradation in recent years (Ezzellet al., 2005). As a result, the LRW was listed on the 2006 Targeted Watersheds Grants funded by the United States Environmental Protection Agency (USEPA, 2005; Harden et al., 2009).

3 Methods

3.1 *LULC classification*

A detailed LULC record has been composited from 1984 to 2010 in this watershed based on the Maximum Likelihood Classification (MLC) of Landsat TM/ETM+ images (Zhu and Li, 2013). This record includes 14 years (1984, 1986, 1988, 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2008, and 2010) of LULC maps in a roughly 2-year temporal interval. Five main classes were classified: water, commercial land, residential land, mixed forest, and agricultural land (Fig. 2a). The accuracy of the classification was assessed by comparing classified LULC classes in 2010 with their corresponding classes identified from Google Earth high-resolution imagery. A kappa coefficient of 85.8% was achieved, suggesting that this record could be used to examine the spatial and temporal patterns of LULC change and assess its long-term hydrological impacts in this critical watershed (Zhu and Li, 2013).

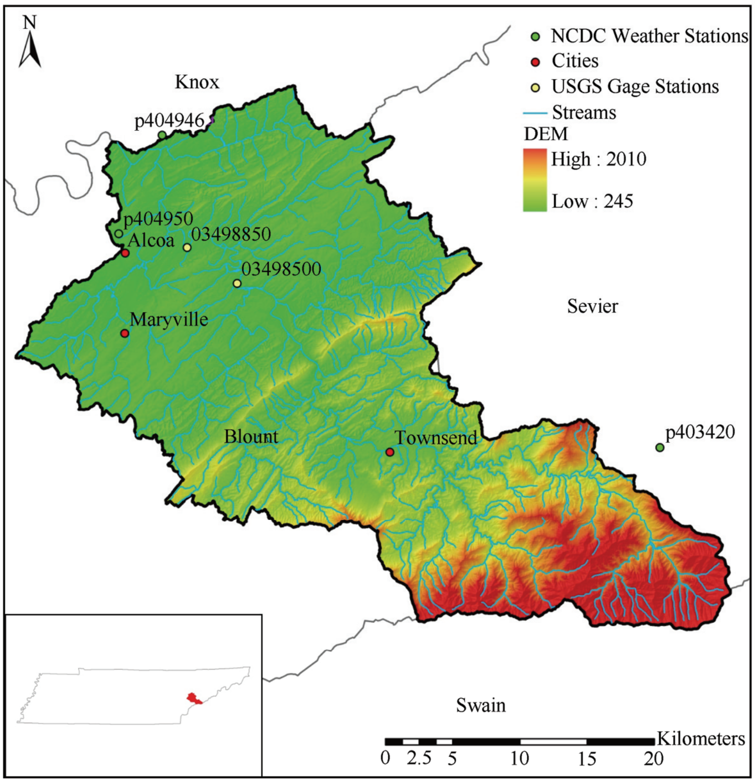

Fig. 1 Location of the Little River Watershed in Eastern Tennessee

3.2 *SWAT*

SWAT is a physically-based distributed hydrological model developed by the USDA-Agricultural Research Service (USDA-ARS) (Arnold et al., 1998; Neitsch et al., 2005; Arabi et al., 2007). It has been widely used to examine the hydrological impacts of LULC change in various U.S. agencies (such as the EPA, NOAA, USDA), universities, and research institutes around the world (Arnold et al., 1998; Fohrer et al., 2001; Gassman et al., 2007; Conaghan, 2010). SWAT operates at a wide range of scales with complex terrain features including various soils, land use, and management conditions over a daily time-step. The simulation of hydrological processes can be divided mainly into two phases, a land phase and a routing phase (Arnold et al., 1998; Neitsch et al., 1999; Weber et al., 2001; Setegn et al., 2010). The land phase controls the amount of water, sediments, nutrients, and pesticide loading to the main channel in each sub-watershed (Neitsch et al., 2005). The routing phase simulates the process of flows, sediment, and nutrient transported in the main channel to reach the outlet of the watershed. The major procedures in SWAT include watershed delineation, Hydrological Response Unit (HRU) analysis, weather data import, parameters input and modification, and SWAT simulation.

SWAT requires a digital elevation model (DEM) to delineate the watershed, divide sub-watersheds, and calculate parameters for each sub-watershed such as slope and slope length (Jha et al., 2007). We used the 30-meter National Elevation Dataset (NED) DEM downloaded from USGS's National Map Seamless Server to delineate the whole watershed into 31 sub-watersheds (Fig. 2b). The soil data was from the State Soil Geographic (STATSGO) Database provided by the Tennessee GIS Spatial Data Server (Fig. 2c). Four meteorological stations close to the watershed were used in SWAT simulation including Gatlinburg 2 SW (403420), Knoxville Exp Station (404946), Knoxville McGhee Tyson Airport (404950), and Mt. Leconte (406328) (Table 1, Fig. 1). The daily precipitation and the maximum and minimum temperatures from 1984 to 2010 were downloaded from the National Climate Data Center. The missing data in the precipitation and temperature records, as well as daily solar radiation, wind speed, and relative humidity, were generated automatically by SWAT (Jhaet al., 2007). The streamflow data were collected from the USGS National Water Information System including two USGS stream gages, USGS 03498500 (the Little River near Maryville) and USGS 03498850 (the Little River above Alcoa), at the upper and lower portions of the watershed (Fig. 2d) (Table 2).

Table 1 **Four NCDC weather stations used in the SWAT model**

Stations	Name	Latitude	Longitude	Elevation	In service	County
403420	Gatlinburg 2 SW	35°41′ N	83°32′ W	443.2 m	01 Aug. 1948 to Present	Sevier
404946	Knoxville Exp Station	35°53′ N	83°57′ W	253.0 m	01 Jan. 1949 to Present	Knox
404950	Knoxville Mcghee Tyson Airport	35°49′ N	83°59′ W	293.2 m	01 Jan. 1893 to Present	Blount
406328	Mt Leconte	35°39′ N	83°26′ W	1979.1 m	01 Jul. 1987 to Present	Sevier

Table 2 **Two USGS stream gaging stations within the Little River Watershed**

Hydrologic unit	Latitude	Longitude	Elevation (m)	Drainage (km^2)	Period	Cooperation
03498500	35°47′07.93″	83°53′04.93″	261	696.71	1951–Present	Maryville, TVA[a]
03498850	35°48′31.52″	83°55′36.03″	251	777	1986–Present	Alcoa

[a] TVA: Tennessee Valley Authority.

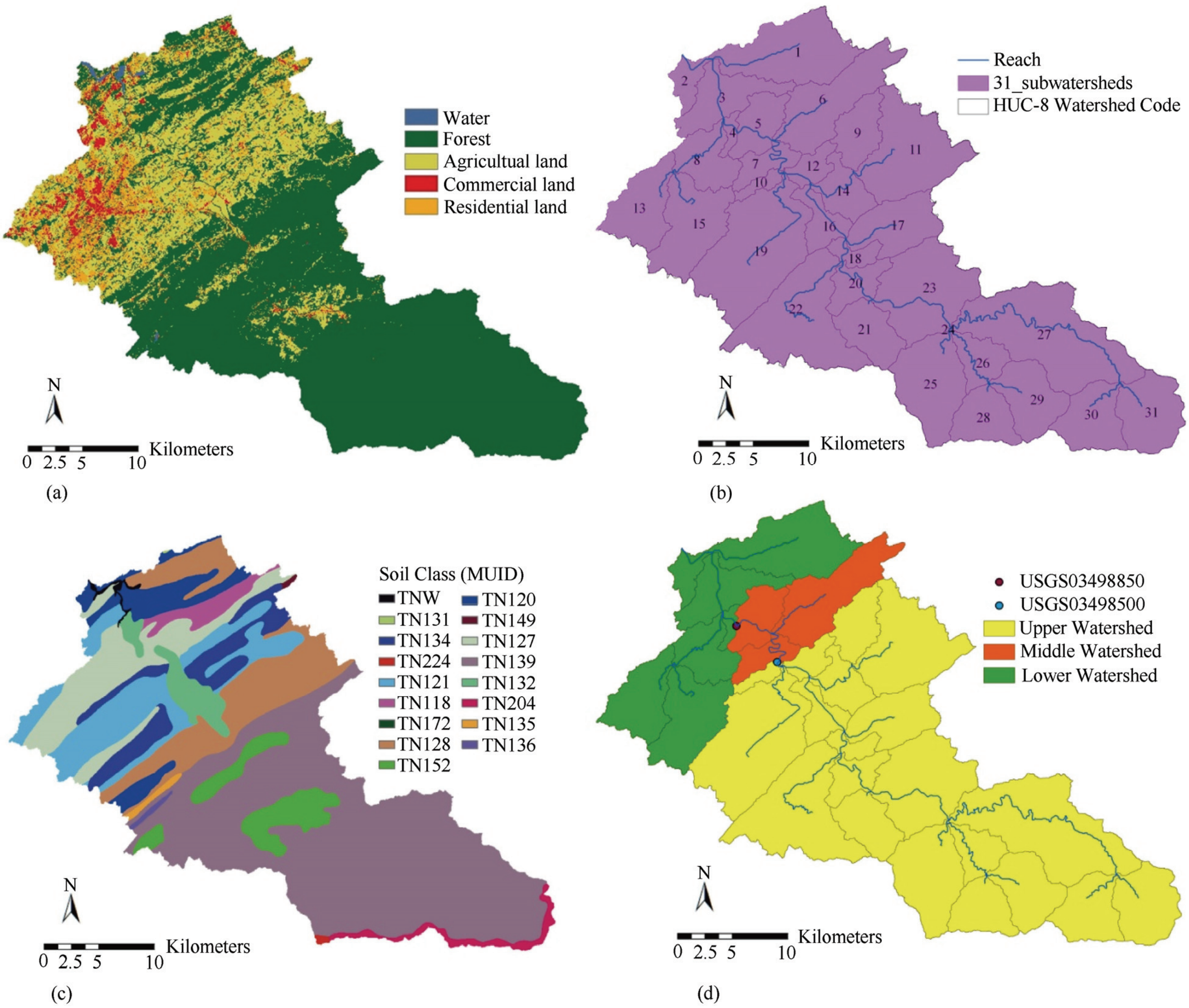

Fig. 2 (a) LULC classification of year 2010. (b) 31 Sub-watersheds within the whole watershed. (c) The distribution of soil types within the watershed (STATSGO). (d) The upper, middle and lower portions of the watershed

Model calibration and validation are critical in using SWAT to simulate the streamflow and NPS pollution. We conducted a sensitivity analysis using the LH-OAT algorithm (Van Griensven et al., 2006; Wang et al., 2008; Setegn et al., 2010) to identify the most sensitive parameters, such as the initial SCS CN II value (Cn2), the baseflow alpha factor (Alpha_Bf), the threshold water depth in the shallow aquifer for flow (Gwqmn), the soil evaporation compensation factor (E_{sco}), the channel effective hydraulic conductivity (Ch_K2) representing surface runoff, groundwater, soil properties, and channel properties (Ghaffari et al., 2009) (Table 3). The Nash-Sutcliffe efficiency (E_{ns}) and the regression coefficient (R^2) between the observed and simulated streamflow were used to assess the goodness of fit of SWAT in both calibration and validation. The Nash-Sutcliffe Efficiency (E_{ns}) was defined as (Nash and Sutcliffe, 1970):

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{1}$$

where n is the number of observations during the simulated period, O_i is the observed value at each time step i, P_i is the predicted value at each time step i, $\overline{O}$ is the average observed value over the simulation period. E_{ns} indicates how well the predicted value fits with the observation (Santhi et al., 2001). The value of 1.0 of E_{ns} represents a perfect match between model simulation and observation, while the value of 0 or below indicates that the prediction is unacceptable (Moriasi et al., 2007). The parameters that are most sensitive to streamflow were repeatedly adjusted until E_{ns}>0.5 and R^2>0.6, the acceptable values suggested by other studies (Santhi et al., 2001).

Table 3List of the top 5 parameters in the sensitivity analysis and their calibrated values for SWAT calibration

Parameter	Description	Rank[a]	Rank[b]	Default	Lower bound	Upper bound	Method	Location	Calibrated value
Cn2(Forest) Cn2(Agricultural land)	Initial SCS CN II value	1st	2nd	36–79 49–84	−25%	25%	Multiplying initial parameter by value (%)	Management (.mgt)	27–59.25 36.75–63
Alpha_Bf	Baseflow alpha factor (days)	2nd	1st	0.048	0	1	Replacement of initial parameter by value	Groundwater (.gw)	0.75
Gwqmn	Threshold water depth in the shallow aquifer for flow(mm)	3rd	3rd	0	0	1000	Replacement of initial parameter by value	Groundwater (.gw)	0
E_{sco}	Soil evaporation compensation factor	4th	4th	0.95	0	1	Replacement of initial parameter by value	General data(.bsn)	0.3
Ch_K2	Channel effective hydraulic conductivity (mm/hr)	5th	5th	0	0	150	Replacement of initial parameter by value	Routing (.rte)	130

[a] rank for sensitivity analysisat USGS 03498500.

[b] rank for sensitivity analysisat USGS 03498850.

3.3 *Evaluation of the Long-term hydrological impacts of LULC change*

After calibrating and validation, SWAT was run using each LULC map as the input to simulate streamflow and NPS pollution from 1984 to 2010. The simulated output for the LULC pattern of year 1984 was used as the baseline to examine streamflow and NPS pollution variations in LULC scenarios of other years. The changing ratio, calculated using the simulated value for a certain year to divide the simulated value of 1984, was used to examine the spatial pattern and the long-term impacts of LULC change on streamflow and NPS pollution.

4 Results and discussion

4.1 *SWAT calibration and validation*

We conducted the calibration and validation for two USGS stream gage stations (USGS 03498500 and USGS 03498850) from the upper and lower stream sections respectively. The upper portion of the watershed is dominated by forest, the middle portion is mainly agricultural, and the lower portion has relatively large amount of urban areas. We used SWAT to simulate daily streamflow from January 1, 2009, to March 15, 2010, based on the land use map of 2010. The period from January 1 to October 9, 2009, was treated as a “warm up” period to stabilize the model. Simulated and observed streamflow data from October 10 to December 31, 2009, were used for model calibration, and data from January 1 to March 15, 2010, were used for model validation.

At the upper stream station (USGS 03498500), the summed simulated and observed stream flows during the calibration period were 28.68 and 29.14 cubic meter per second (cms), respectively. The best calibration we can achieve is E_{ns} of 0.847 and $R^2$of 0.855. The total simulated and observed streamflows during the validation period were 24.81 and 26.15 cms, respectively, with an E_{ns} of 0.728, and R^2 of 0.733 (Table 4; Fig. 3a, b). At the lower stream station (USGS 03498850), the total simulated and observed stream flows during the calibration period were 31.06 and 31.43 cms, respectively, with an E_{ns} of 0.838 and R^2 of 0.852. The total simulated and observed streamflows during the validation period were 27.94 and 29.03 cms, respectively, with an E_{ns} of 0.712 and R^2 of 0.713 (Table 4; Fig. 3c, d).The high E_{ns} and R^2 values in both calibration and validation periods indicated that, with calibrated parameters, the SWAT can be used to simulate the streamflow and quantify the long-term hydrological impacts of the LULC change.

Table 4 Daily calibration/validation results of two USGS stations

Stations	Period	Simulated mean ($m^3 s^{-1}$)	Observed mean ($m^3 s^{-1}$)	E_{ns}	R^2	Re (%)
USGS 03498500	Calibration	28.68	29.14	0.847	0.856	1.56
	Validation	24.81	26.15	0.728	0.734	5.12
USGS 03498850	Calibration	31.06	31.43	0.838	0.852	1.19
	Validation	27.94	29.03	0.712	0.714	3.76

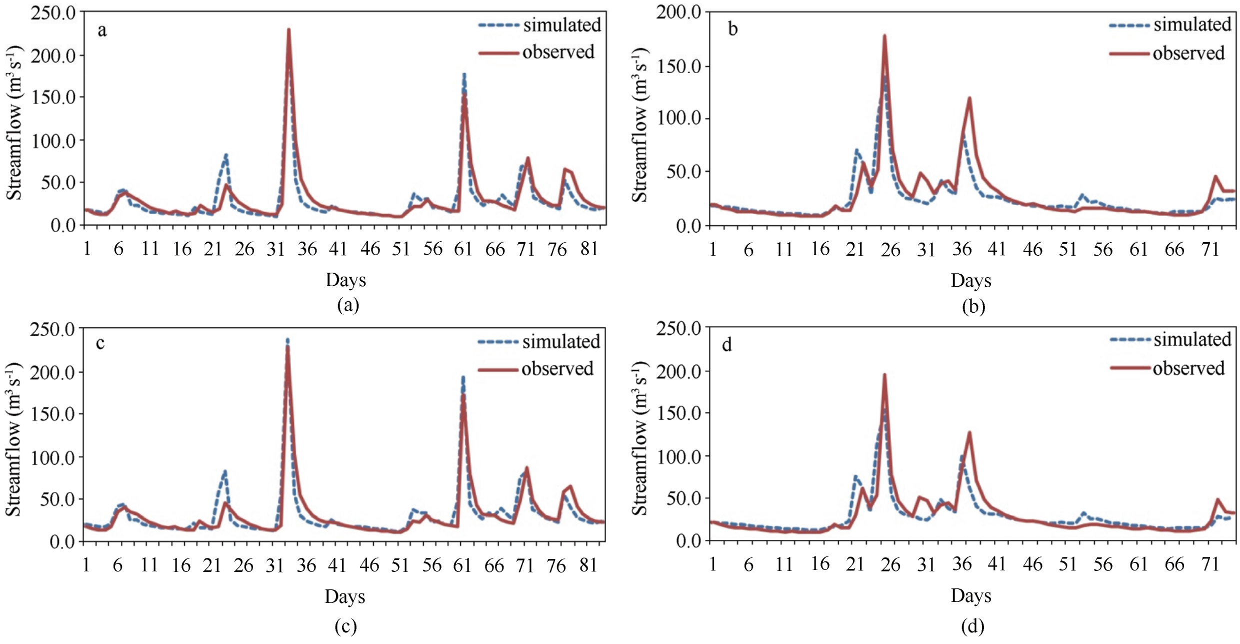

Fig. 3 Comparison between simulated and observed daily stream flow: (a) Station USGS 03498500, the calibration period; (b) Station USGS 03498500, the validation period; (c) Station USGS 03498850, the calibration period; (d) Station USGS 03498850, the validation period

4.2 *LULC change and its impact on stream flow*

As discussed in Zhu and Li (2013), the Little River Watershed experienced obvious LULC change from 1984 to 2010. The increase in urban areas mainly occurred around the cities of Maryville and Alcoa due to the population growth in the Blount County. From 1984 to 2010, residential and commercial lands increased from 5.2% and 1.0% to 8.3% and 2.8%, respectively. In contrast, agricultural land decreased from 28.3% to 18.9%. Forest increased from 65.0% to 69.5% in this period due to the protection effort of the national park, as well as the natural replacement of abandoned agricultural land.

SWAT simulation suggested a total 3% streamflow increase from 1984 to 2010 for the whole watershed. The increase was relatively consistent through the whole period, except for that it was more stable in 1991–1995 and rapid in 1984–1986 and 2008–2010 (Fig. 4a). Bar charts in Fig. 5 illustrate a distinct spatial pattern of the streamflow increase rate for each sub-watershed in different years. Stream flows from sub-watersheds located within the national park were relatively stable in 1984–2010, whereas >10% streamflow increase occurred at sub-watersheds around the cities of Maryville and Alcoa. Moderate streamflow increase (0.4%–5.3%) also occurred in the middle and lower portions of the watershed where agricultural lands were converted to urban areas.

Regression analysis show a statistically significant and positive relationship ($R^2 = 0.94$, $P < 0.001$) between streamflow and the percentage of urban areas from different years (Fig. 6a). This indicated that the streamflow increase is driven mainly by urban expansion especially in the lower portion of the watershed around the cities of Maryville and Alcoa. However, urban areas only account for <12% of the whole watershed and a slight increase in forest may reduce the effect of streamflow increase causing by urban expansion, resulting in just a minor increase (3%) in streamflow of the whole watershed.

4.3 *Impacts on NPS pollutions*

SWAT simulation also suggested considerable changes in NPS pollutions from 1984 to 2010 due to the LULC change. Although modeled sediment load in 1989, 1993, and 2003, nitrogen load in 1995, and phosphorus load in 1991, 1995, and 2003 increased slightly, the overall trend of these pollution loads decreased from 1984 to 2010. Using the simulation results of 1984 as the baseline, from 1984 to 2010, the sediment, nitrogen, and phosphorus loads decreased 34.6%, 10.4%, and 10.0%, respectively (Fig. 4b, c, and d). Spatially, the decrease in sediment, nitrogen, and phosphorus loads mainly occurred in the middle and lower portions of the watershed

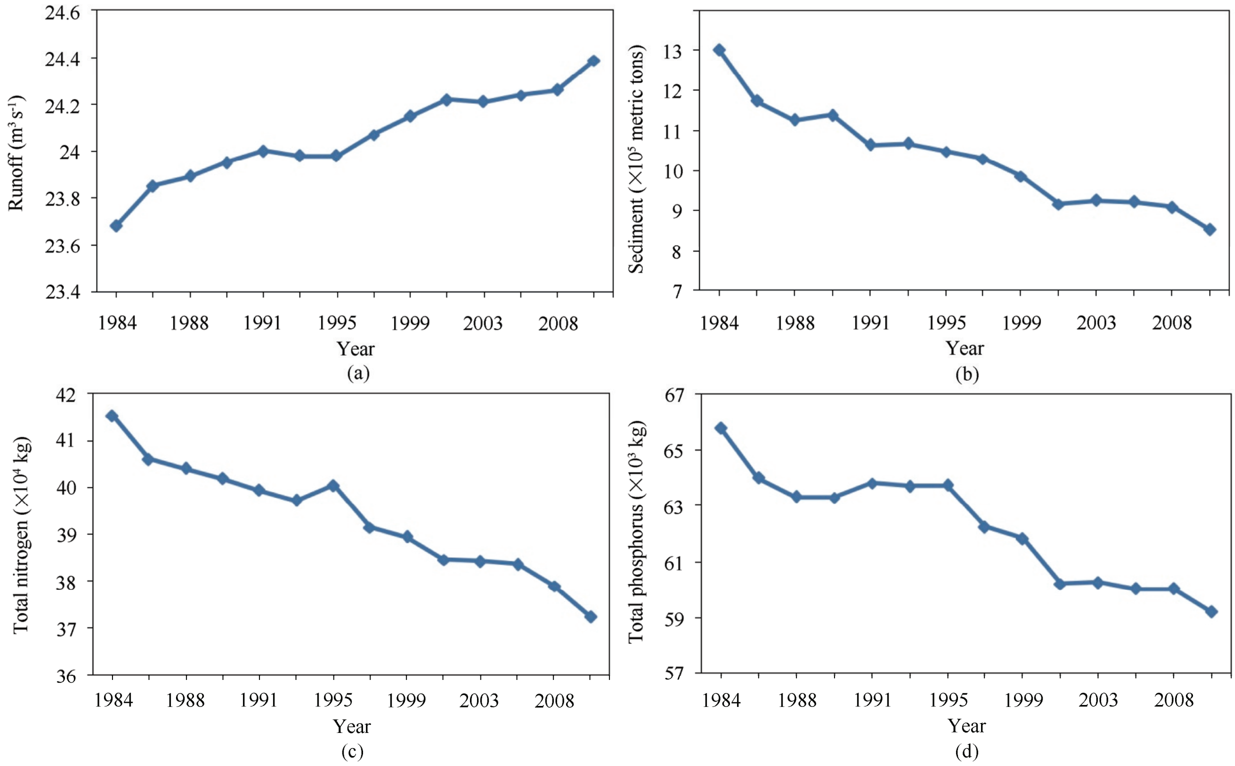

Fig. 4 Variations in simulated streamflow and NPS pollutions of the whole watershed from 1984 to 2010: (a) Stream flow; (b) Sediment yield; (c) Total nitrogen load ; (d) Total phosphorus load

where agricultural lands were replaced by urban and forest (Fig. 7). Positive relationships ($R^2 > 0.9$, $P < 0.001$) were obtained between each pollution load and the percentage of agricultural land (Fig. 6b, c and d), suggesting that the reduction of NPS pollutions is probably resulted from the decrease in agricultural land. The simulated decreasing trend in sediment and nutrients is consistent with the report from TVA (2003) stating that the reductions in Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorous (TP) loads from agriculture exceeded the increases from urban areas in the Little River Watershed. However, we hesitate to draw this as a firm conclusion because we did not perform the model calibration and validation for NPS pollutions due to the lack of observed data.

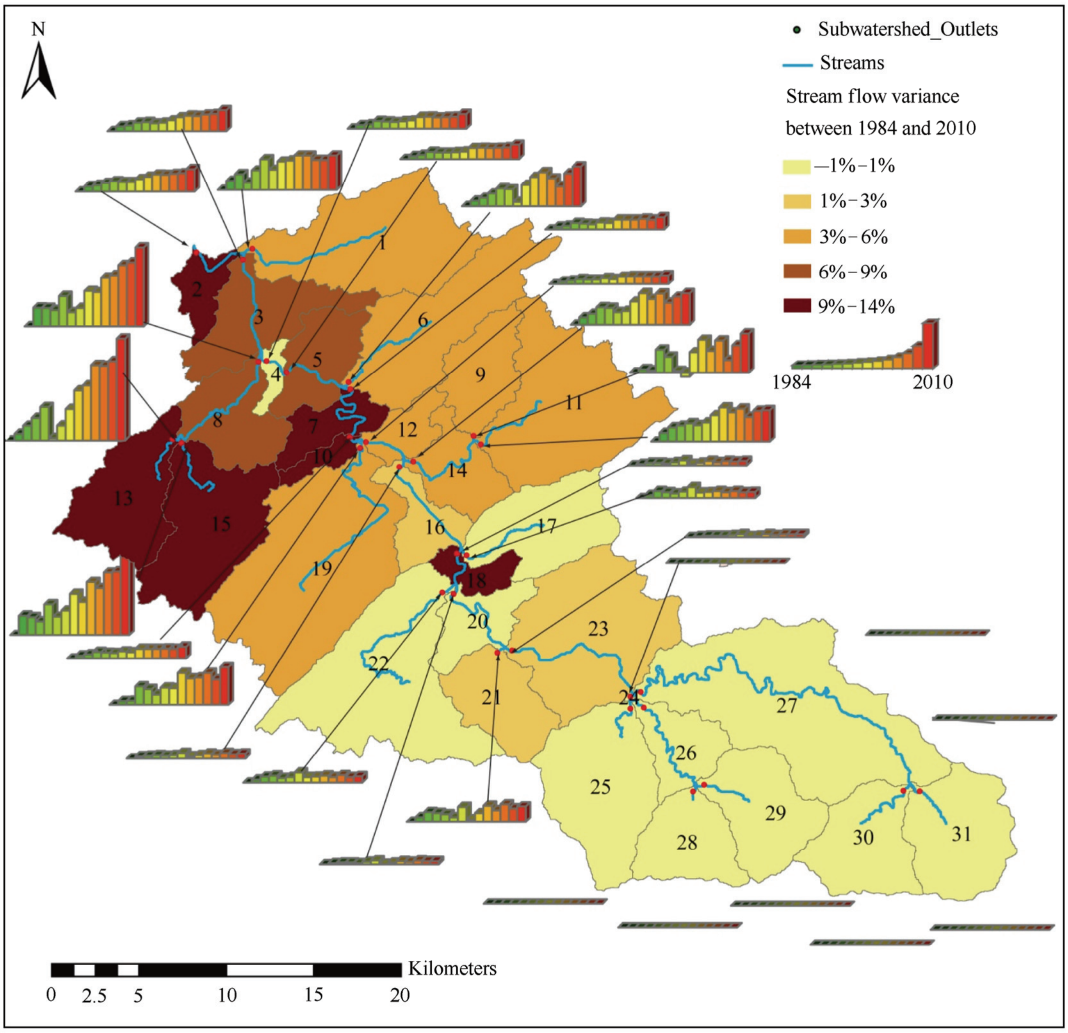

Fig. 5 Spatio-temporal changing rate of streamflow at each sub-watershed outlet and the comparison between streamflows in 2010 and 1984 for different sub-watersheds

Simulated results for NPS pollutions may be problematic because of the limitations in SWAT and our simulation strategy. In this work, we simply used SWAT to simulate NPS pollutions for different LULC scenarios without the consideration of LULC transitional periods, such as the construction phases of urban development. However, sediment and nutrient loads may be mainly generated during the construction phases. For example, several studies indicated that the construction can increase the soil erosion rate > 4,000 times higher than the preconstruction rates (McClintock and Harbor, 1995; Harbor, 1999). In addition, SWAT incorporated a Modified Universal Soil Loss Equation (MUSLE) to estimate sediment load generated from the watershed. However, it does not account for sediment generated from the streams (Neitsch et al., 2005). Studies suggested that stream bank erosion may contribute a large amount of sediment to the Little River (Harden et al., 2009, 2010). As a consequence of continuous urban expansion, the increase in streamflow and flash flooding may accelerate bank erosion and carry more sediment and nutrients into the streams. Therefore, SWAT simulations would more likely underestimate NPS pollution loads, especially the sediment component.

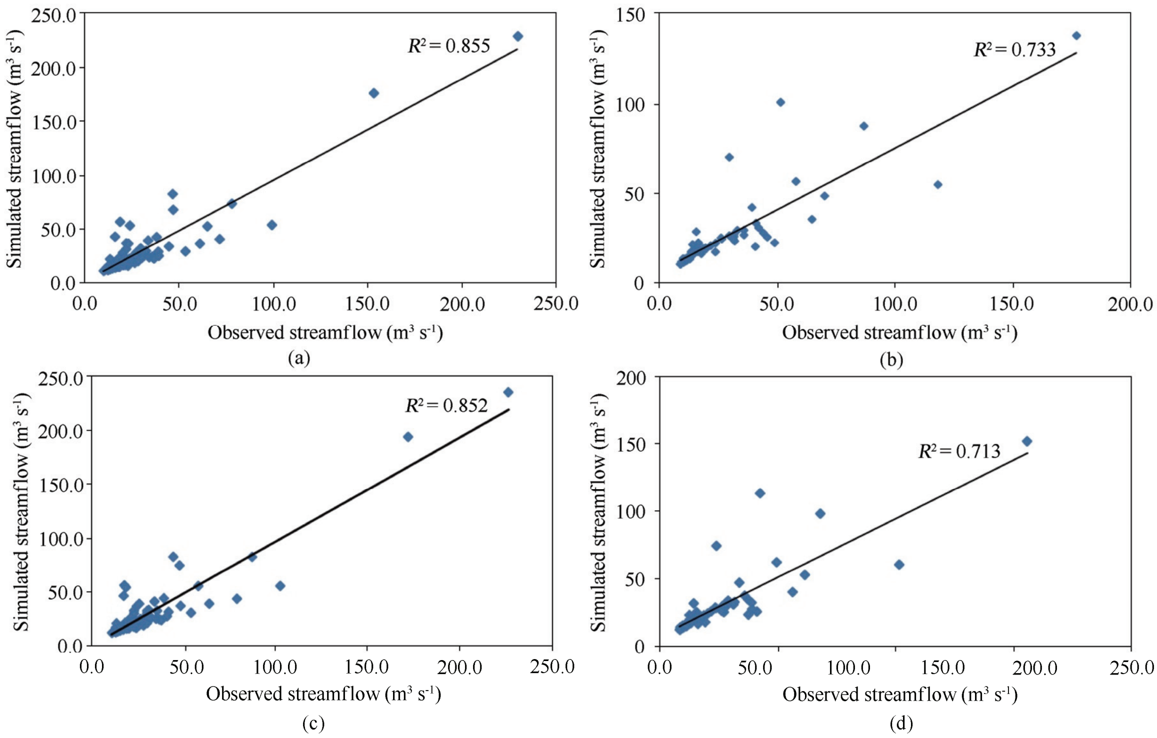

Fig. 6 Relationship between the increase in streamflow and the percentage of urban areas (a) and relationship between the reduction in sediment (b), nitrogen (c), and phosphorus (d) loads and the percentage of agricultural land

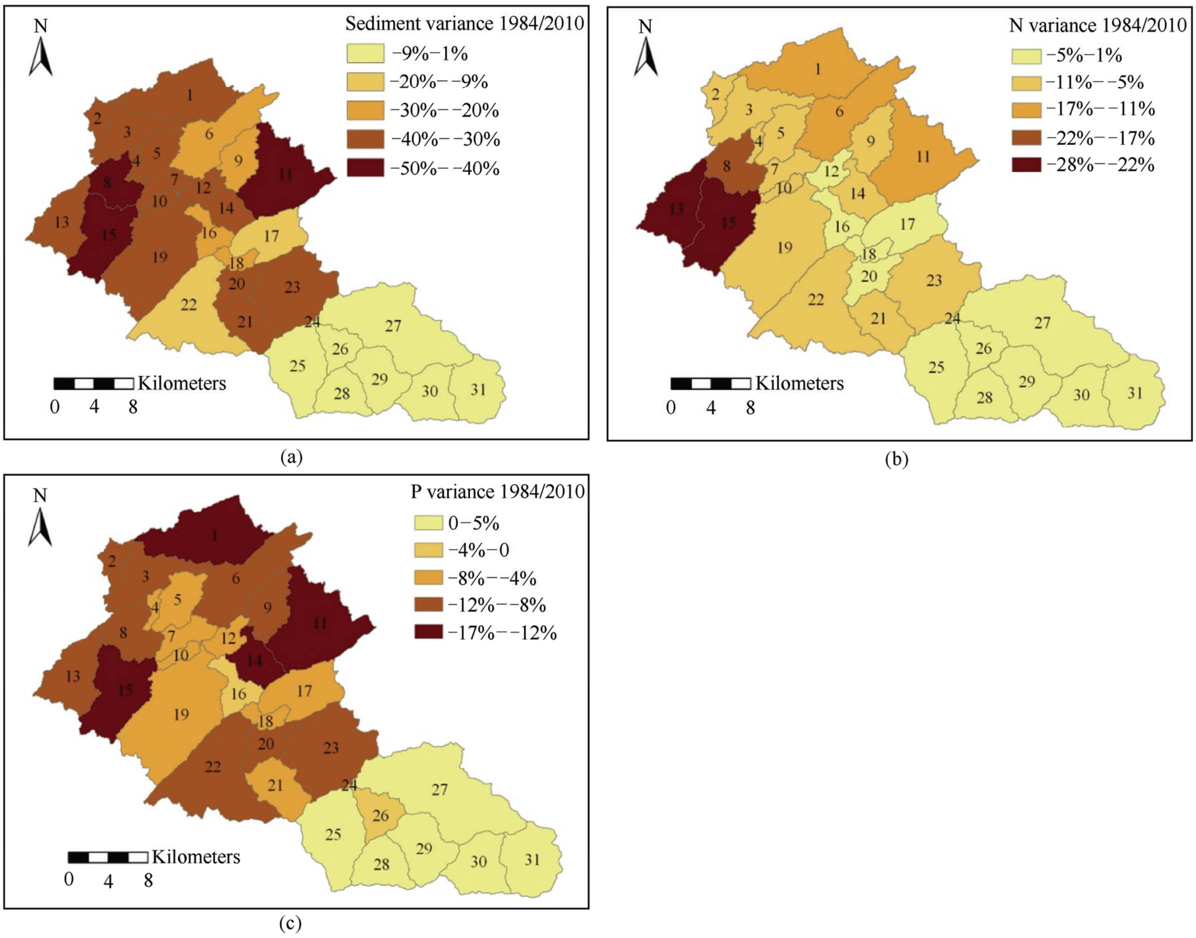

Fig. 7 Comparisons of sediment yield (a), total nitrogen (b), and total phosphorus (c) between 1984 and 2010

The LULC dataset used in this study may also introduce uncertainties in the SWAT simulations. In particular, the LULC datawe used did not differentiate cropland and grassland (pasture and hay fields) and the model simply treated them as one class. This treatment may introduce uncertainties because cropland and grassland have distinct hydrological impacts especially on NPS pollutions. Further studies to differentiate these two LULC classes would improve the simulation results.

5 Conclusions

In this paper, SWAT was applied to examine the long-term hydrological impacts of LULC change in the Little River Watershed using a detailed LULC record from 1984 to 2010. The model was first calibrated and validated using observed streamflow data in 2010 and then simulated using different LULC scenarios to quantify the long-term hydrological impacts due to the LULC change. Model simulation indicated just an overall of 3% increase in streamflow for the whole watershed from 1984 to 2010, but with a distinct spatial pattern. Almost no streamflow increase occurs in the upper portion of the watershed within the national park, whereas >10% streamflow increase was observed in the lower portion of the watershed, especially in areas close to cities. The increase in streamflow is most likely driven by urban expansion although the slight increase in forest may reduce the effect of streamflow increase causing by urban development. SWAT simulations also suggested 34.6% sediment and about 10% nutrient reduction from 1984 to 2010, closely related to the decrease in agricultural land. However, without calibration and validation, the simulation of the sediment and nutrient loads may be problematic because SWAT mainly simulates the static status of LULC patterns, but LULC transitional periods, such as construction phases, may generate more sediment and nutrient loads. In addition, the simulation also did not account for the sediment and nutrients generated from stream bank erosion.

Acknowledgments

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